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BULLETIN No. 8 SEPTEMBER 1906

TESTS OF CONCRETE: I. SHEAR; II. BOND.

BY ARTHUR N. TALBOT, PROFESSOR OF MUNICIPAL AND SANITARY ENGINEERING AND IN CHARGE OF THEORETICAL AND APPLIED MECHANICS.

I. SHEAR.

Reference to current engineering literature and discussions will show that there exists in the minds of engineers quite diverse notions of the shearing resistance of concrete. Values as low as the tensile strength of the concrete are cited; others name a shearing resistance nearly as great as the compressive strength of the concrete. It seems evident that these divergent estimates must be due to inconsistent experimental methods or to improper conceptions of the nature of shearing action.

Shear is defined to be the action of two equal and oppositely directed forces whose lines of action are in planes very close together. Manifestly, in the actual application of forces to structures or even to test pieces, the applied forces are not in adjacent planes, and the shearing forces used in the analysis and calculation are forces which exist by virtue of the mechanics of the problem. The shearing stresses in concrete test pieces are discussed on the basis of some distribution throughout the section, generally a uniform or nearly uniform distribution. The importance of determining this distribution is not usually recognized. Shear should be differentiated from cutting action, in that the latter begins at the surface and involves, in some degree at least, a gradual tearing or detrusive action and a concentration of the force at a single point. Shear should also be distinguished from the phenomena which may accompany it, as bearing action, diagonal tension, etc. In fact, the difficulties surrounding the determination of the shearing resistance of concrete are due largely to the accompanying cutting action, bearing pressures, and beam stresses involved in the test. In the breaking of reinforced concrete beams, shearing failures have been confused with diagonal tension failures (see Bulletin No. 4, p. 25), and calculations made from the results of such beam tests are evidently a source of low values given in texts and in the building ordinances of many of the cities of the country.

Fig. 1 illustrates a common conception of shear. The shearing force is considered to act along the line AB, and the shearing resistance is assumed to be uniformly distributed over the section on this line. Evidently these assumptions do not give the real action. Cutting action begins at the surface. The fibers are pushed inward immediately in front of the cutting edge. As this impression is increased, the bearing pressure is extended over a greater surface of the tool, though not uniformly so distributed, and the resultants of the applied forces will be moved away from the line AB. This separation of the applied forces gives a couple, with resulting beam action and horizontal and diagonal tensile and compressive forces. It is evident that the bearing action and resulting impression modify conditions and also that the shearing stresses are not uniformly distributed over the section, and that cutting action may injuriously affect results. A little calculation will show that the bearing pressure for a thin tool would exceed the resistance of the concrete. Besides, a test piece could not be held in the position shown, and a further support will be necessary.

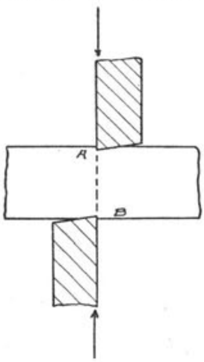

FIG. 1. COMMON CONCEPTION OF SHEAR.

Fig. 2 shows a method which has been proposed and which is open to similar objections. Fig. 3 shows a test piece arranged to get double shear. Evidently the bearing bars, which are only about ¼ in. wide, will produce such high bearing pressures as to cause cutting action or at least cutting stresses. Fig. 4 is a beam form of test piece. Here the test is complicated by flexural stresses and by deflection or opposition to flexure. The attempts at clamping the ends of the test piece to approximate to a restrained beam, such as are hereinafter described, are also open to objection. Punching tests do not give ideal conditions, as will be seen in the tests of plain plates.

It will be seen that these methods of making tests and of applying the load are open to some objection or other. What is wanted is to get as near ideal conditions as is possible and to approach the conditions which exist in structures under investigation. Take for illustration vertical shear in beams, which forms one of the most common and most important applications for the values to be obtained for shearing resistance. In this case, bearing stresses have little effect. Cutting action does not exist. The vertical shearing stresses are nearly uniformly distributed over the section below the neutral axis and vary only moderately over the compression area. (See Bulletin No. 4, p. 20.) Again attention should be called to the inconsistency of using the terms "shear failure" and "diagonal shear failure" in the case of beams failing by diagonal tension.

This bulletin records the results of shear tests made in the Laboratory of Applied Mechanics of the University of Illinois, together with statements of other available data. It is known that the methods used in the tests and the forms of test pieces used are open to objection, but investigations of this kind are experimental in methods as well as in materials, and the experiments in methods are of themselves of value. It is believed, too, that the results, when compared with those made elsewhere, will go toward establishing the general or comparative value of the shearing strength of concrete, and that no end would be subserved in holding the results for more complete data.

The tests were made principally as thesis work. The tests of 1905 were made by C. S. O'Connell and J. E. Shoemaker of the class of 1905 in civil engineering; those of 1906 by J. E. Schoeller and N. E. Seavert of the class of 1906. These men are entitled to credit not only for the care and industry displayed in their work but for the thought and study given to the problem. Acknowledgment is made to V. R. Fleming, 1905, for aid in the preparation of this bulletin.

DATA FROM VARIOUS SOURCES.

Before taking up the University of Illinois tests, a few pages will be devoted to data taken from various sources and to a brief examination of these data.

It has already been stated that the prevailing notion among engineers is that the shearing strength of concrete is comparatively low. The text-books on concrete and reinforced concrete quote values equal to, or a little more than, the tensile strength of concrete and but a small part of the compressive strength. In the following data, instead of referring to the original publication of the experiments, reference is generally made only to the books which may be available to the general reader.

A set of tests on shearing strength of mortar which have been frequently quoted was made by Bauschinger* in 1878. The test specimens were taken from test pieces 2.4 in. × 4.8 in. × 12 in. which had been broken in flexure. The results were interpreted to show that the shearing strength of the mortar was 20% greater than the tensile strength of similar mortars. It seems probable that in the method of testing used tension and not shear was the controlling element. Results of later tests seem to indicate that these values are not representative of the resistance of portland cement mortar in simple shear.

Marsh† quotes Feret as concluding "that the ultimate shearing resistance is proportional to that for compression, and obtains the relation that the shearing resistance is from 0.16 to 0.20 of the compressive strength; this would give us, taking 2175 pounds per square inch, (the mean compressive resistance at from four to six weeks) a shearing strength of from 350 to 435 pounds per square inch, and at a period of three months from 415 to 520 pounds per square inch".

Marsh also makes the following statement: "In a paper presented at the 1901 Budapest Congress, M. Considère gives the value of the resistance of concrete to shearing deduced from M. Mesnager's experiments as from 20% to 30% higher than the tensile resistance; this gives, taking the values from 260 to 285 pounds per square inch, as the mean at a period from four to six weeks, and 310 to 340 pounds per square inch at three months, which are

* Sabin's Cement and Concrete, p. 328. Falk's Cements, Mortars and Concretes, p. 27.
† Marsh's Reinforced Concrete, p. 222.

TABLE 1.*

STRENGTH OF PORTLAND CEMENT MORTARS.

BY R. FERET.

Item	Approximate Proportion by Weight		Ultimate Strength lb. per sq. in.			Ratio of Shear to Compression
	Cement	Sand	Shear	Tension	Compression	
1	1	18.6	170	69	240	.71
2	1	9.9	570	146	870	.66
3	1	6.9	1070	212	1540	.70
4	1	5.2	1440	258	2350	.61
5	1	4.1	2000	314	3320	.60
6	1	3.2	2560	367	4170	.61
7	1	2.5	2790	421	5210	.54
8	1	1.8	3580	480	5970	.60
9	1	1.2	3930	537	6670	.59
10	1	0.7	3640	563	6810	.65
11	1	12.9	256	81	310	.83
12	1	7.0	669	182	950	.70
13	1	5.0	1040	240	1510	.69
14	1	4.1	1350	278	1990	.68
15	1	3.1	1810	320	2720	.67
16	1	2.5	2250	368	3430	.66
17	1	2.0	2650	415	4380	.61
18	1	1.4	2750	521	5440	.50
19	1	0.9	3580	541	6100	.59
20	1	0.5	3540	602	6720	.53
21	1	12.3	156	67	160	.97
22	1	5.8	370	126	540	.69
23	1	3.5	768	214	1230	.62
24	1	2.4	1410	302	1940	.73
25	1	1.8	2130	364	2840	.75
26	1	1.3	2570	436	3710	.69
27	1	1.0	2750	510	5000	.55
28	1	0.7	3070	574	5760	.53
29	1	0.5	3570	647	6500	.55
30	1	0.3	4120	691	7110	.58
31	1	5.0	1720	328	2350	.73
32	1	3.0	3100	450	4010	.77
33	1	2.0	3070	518	4810	.64
34	1	3.0	....	456	3640	...
35	1	0.0	3680	698	8040	.46

* Taken from Concrete, Plain and Reinforced, by Taylor and Thompson, p. 136.

considerably below those found by M. Feret. Many authors assume that the resistance of concrete to shearing is less than its resistance to tension, and consequently give it a much lower value, but this assumption appears to be erroneous."

Taylor and Thompson* give data from Feret's investigation which indicate a much higher shearing strength for mortar than that given in the preceding paragraph. Table 1 gives the shearing, tensile, and compressive strength of these mortars. It will be seen that the shearing strength ranges from 46% to 97% of the compressive strength and is three to six times the tensile strength.

The method of testing (see Fig. 2) may be open to criticism. The specimen is subjected to single shear, and the small bearing area may produce excessive compressive stresses. Tensile stresses may govern the failure.

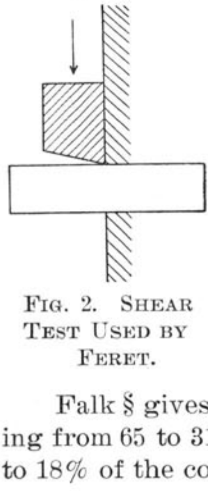

FIG. 2. SHEAR TEST USED BY FERET.

Considère † states that the experiments made by Mesnager tend to show that the resistance of mortar to shearing exceeds its tensile resistance as it is determined by the usual tests. Tests, which may be too few to allow of general conclusions, have shown a difference of 20% to 30% between these two resistances. Marsh ‡ quotes Considère as applying the same statement to concrete.

Falk § gives values of the shearing strength of concrete ranging from 65 to 314 pounds per square inch, and amounting to 10% to 18% of the compressive strength of the concrete.

* Taylor and Thompson's Concrete, Plain and Reinforced, p. 136, taken from "Etudes sur la Constitution Intime des Mortiers Hydrauliques", in Bulletin de la Societe D'Encouragement pour L'Industrie Nationale, 1897. Series 5, Vol. 11, p. 1591.

† Considere's Reinforced Concrete, translated by Moisseiff, p. 104.

‡ Marsh's Reinforced Concrete, p. 222.

§ Falk's Cements, Mortars and Concretes, p. 95. Figure showing method of test, p. 87.

TABLE 2.*

SHEARING AND CRUSHING STRENGTH OF 1-3-5 CONCRETE.

BY M. S. FALK.

No.	Ultimate Crushing Resistance		Ultimate Shearing Resistance		Ratio of Shear to Compression
	Of 6-inch cube lb. per sq. in.	Age days	lb. per sq. in.	Age days	
1	1870	177	195	169	.10
5	....	...	314	165	...
6	1246	164	166	164	.13
8	1196	157	187	157	.15
10	863	151	158	151	.18
22	922	128	104	128	.11
23	600	128	65	128	.11

Table 2 summarizes the data. The method of making the shearing test (Fig. 3) is open to criticism, particularly in that the high bearing stresses cause a cutting action, and the failure of the specimens can hardly be said to be due to shear. The values obtained can not be considered to be representative of the shearing strength of concrete.

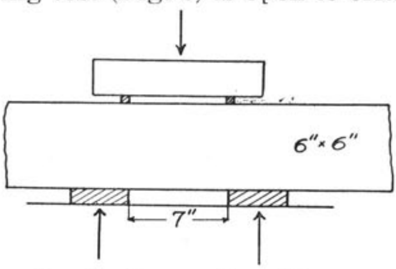

FIG. 3. SHEAR TEST USED BY FALK.

Tests made by Zipkes† on prisms 7 × 7 × 15.8 in. gave values of 357 pounds per square inch for shearing strength of concrete 50 days old. The prisms were supported but not clamped, and the conditions resemble beam failure so much that the results can not be considered to represent ordinary shearing strength. Fig. 4 shows the form of test specimen.

* Taken from Cements, Mortars and Concretes, by Falk, p. 95.

† Beton und Eisen, January, 1906, p. 15, et seq. Translation printed in Cement, March, 1906.

Tests on slotted concrete beams reported in the same article are open to the objection that web stresses other than shearing stresses probably were the cause of the failure.

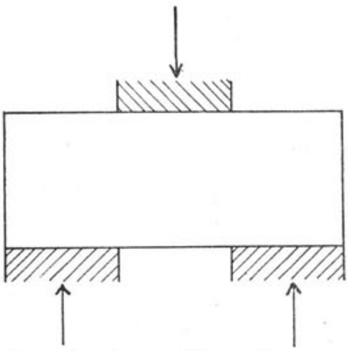

FIG. 4. SHEAR TEST USED BY ZIPKES.

A valuable set of tests on the shearing strength of concrete was made at the Massachusetts Institute of Technology under the direction of Professor Spofford and the auspices of the Joint Committee on Concrete and Reinforced Concrete in 1905. A summary of the data is given in Table 3. Three grades of concrete were used and test pieces were stored in air and also in water. The cylindrical test piece was 5 in. in diameter and $15\frac{1}{2}$ in. long and the ends were securely clamped above and below in cylindrical bearings. The load was applied along a length of $5\frac{7}{16}$ inches of a semi-cylindrical bearing block. This manner of testing permitted the test piece to break first as a beam but final failure was by shear. Tensile stresses may have affected the results somewhat; if so, the values given are less than the true shearing stength.

TABLE 3.

SUMMARY OF SHEAR TESTS.

MADE AT MASSACHUSETTS INSTITUTE OF TECHNOLOGY.

Kind of Concrete	Method of Storing	Shearing Strength lb. per sq. in.			Crushing Strength lb. per sq. in.	Ratio of Shear to Compression
		Maximum	Minimum	Average		
1-2-4	Air	1630	960	1310	2070	0.63
1-2-4	Water	2090	1180	1650	2620	0.63
1-3-5	Air	1590	890	1240	1310	0.94
1-3-5	Water	1380	840	1120	1360	0.32
1-3-6	Air	1450	950	1180	950	1.25
1-3-6	Water	1200	1030	1120	1270	0.88

MATERIALS, TEST PIECES AND TESTS.

The materials, forms of test pieces, method of testing and phenomena of the tests made at the University of Illinois in 1905 and 1906 will now be described.

Materials.—The broken stone used in the 1905 tests was Kankakee limestone screened through a 1-in. and over a $\frac{1}{4}$-in. screen. It was taken from the lot described more fully in Bulletin No. 4. The stone for the 1906 tests was similar in character but somewhat harder. The sand was coarse mortar sand, that used in the 1905 tests being the same as that described in Bulletin No. 4 and that used in 1906 being similar in character. The cement used in 1905 was the mixture of American portland cements furnished by the Joint Committee on Concrete and Reinforced Concrete described in Bulletin No. 4. The tensile strength of the neat cement was 723 pounds per square inch at age of 7 days, and 1-3 mortar gave 354 pounds per square inch at 7 days and 533 pounds per square inch at 75 days. The cement used in 1906 was similar in character.

Test Pieces.—As has already been stated, it is extremely difficult to make a test of concrete which will determine the shearing strength. Other stresses, tensile, bearing, and web stresses complicate the problem, and their action may be the controlling element of failure even when shearing action is the apparent cause. The form of test piece to be used was the first point to study, and one purpose of these tests was to find the effect of different forms of test pieces and learn what form is open to the least objection. Two methods of testing were used. In the first, a hole was punched in a concrete plate or block, and this method will be referred to as a punching test. The second method consisted in breaking a short concrete beam which was restrained at the ends. This method will be referred to as the restrained beam test.

Three forms of test pieces were used in the punching tests,—1. plain concrete plate; 2. recessed concrete block; 3. reinforced recessed concrete block. As was to be expected, the plain concrete plate failure indicated that induced tensile stresses contributed to the failure, and the other test pieces were contrived in an attempt to overcome this defect. A cylindrical die $5\frac{7}{8}$ in. in diameter was used in the punching tests. Fig. 5 (a) shows the dimensions of the plain concrete plate. In the recessed block, shown at (b),

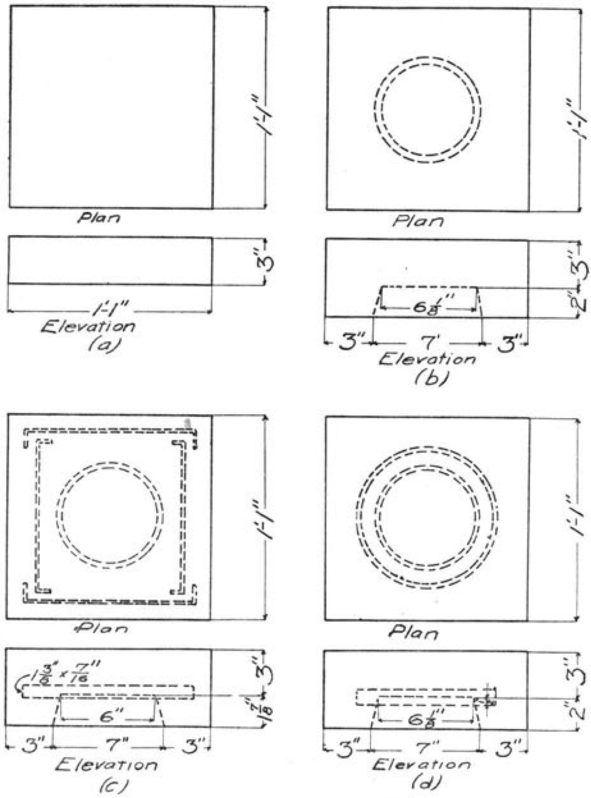

FIG. 5. FORMS OF SHEAR TEST PIECE. (a) PLAIN CONCRETE PLATE. (b) RECESSED BLOCK. (c) and (d) REINFORCED RECESSED BLOCKS.

the shearing area is the same, and the hollow space at the bottom is given a draft in order to facilitate drawing the form. This test piece is better fitted to withstand the tensile stresses developed during the punching operation. Fig. 5 (c) and (d) show the reinforced recessed blocks. A reinforcement of steel was embedded in the concrete. In two specimens tested in 1905 four bent bars, $\frac{7}{16} \times 1\frac{3}{8}$-in., were placed as shown in Fig. 5 (c), and in two specimens, eight bent rods, $\frac{1}{4}$-in. square and twisted, were similarly placed.

In making the tests, the test specimens were placed on a bed plate 1 inch thick, having an opening 6 inches in diameter in the center. The load was applied through a spherical bearing block, and a die 5⅞ inches in diameter placed on the test specimen formed the punching tool. Plaster of paris coatings were used on all bearing surfaces.

The test piece for the restrained beam test (Fig. 6) was 4 × 4 in. in cross section and 13 inches long. The cast-iron bed plate was faced above and below, as were the two plates at the top.

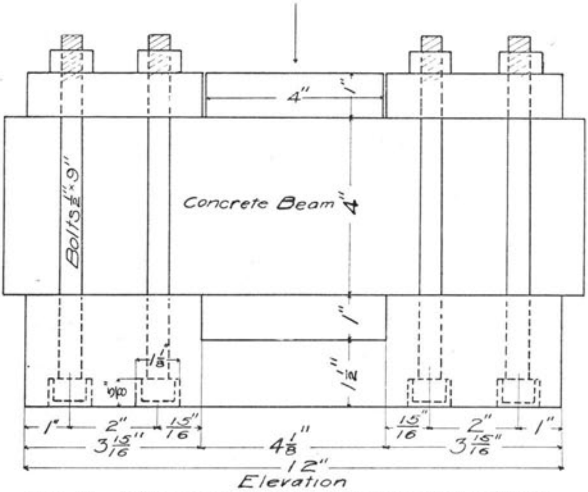

FIG. 6. RESTRAINED BEAM SHEAR TEST PIECE.

TABLE 4.*

COMPRESSIVE STRENGTH OF 6-INCH CUBES.

1905 TESTS. 1-3-6 CONCRETE.

Concrete as in	Method of Storing	Age days	Compression Area sq. in.	Ultimate Load pounds	Compressive Strength lb. per sq. in.
Beam No. 35	Air	66	36	48000	1330
	Air	66	36	47980	1330
	Air	66	36	57400	1590
Beam No. 44	Air	67	36	38400	1065
	Air	67	36	39800	1105
	Air	67	36	29400	816
Beam No. 65	Air	59	36	47200	1310
	Air	59	36	41600	1156
	Air	59	36	48850	1355
Average					1230

* Taken from Bulletin No. 4, p. 32.

The bolts clamped the beam tightly on the bed plate. Plaster of paris coatings were used on all bearing surfaces. Fig. 10 shows the apparatus in testing machine.

TABLE 5.

COMPRESSIVE STRENGTH OF 6-INCH CUBES.

1906 TESTS. 1-3-6 CONCRETE.

Ref. No.	Method of Storing	Age days	Compression Area sq. in.	Load in pounds		Compressive Strength lb. per sq. in.
				At First Crack	Ultimate	
	Damp sand	60	37.9	70000	73200	1930
1	Damp sand	60	37.5	72000	73500	1958
	Damp sand	60	36.4	73500	74500	2045
	Damp sand	60	37.9	58000	86200	2274
2	Damp sand	60	37.2	67000	79500	2135
	Damp sand	60	36.4	48000	75600	2072
	Damp sand	61	37.5	92000	100700	2685
3	Damp sand	61	37.1	92000	113600	3060
	Damp sand	61	37.1	78000	109200	2945
	Damp sand	59	37.1	70400	101000	2722
4	Damp sand	59	37.1	84000	101800	2740
	Damp sand	59	37.9	74000	97400	2568
Average	....	....	....	....	....	2428
	Damp sand	60	37.1	59600	65800	1773
5	Damp sand	60	37.1	53100	66500	1791
	Damp sand	60	36.8	50100	58900	1600
Average	....	....	....	....	....	1721

Compressive Strength of Concrete.—An effort was made to find the compressive strength of concrete in order that comparisons with the shearing strength might be made. The method of making and storing the test pieces was not altogether satisfactory, and for this reason a comparison of strength can not be considered entirely trustworthy. All the cubes tested were 6-in. cubes. In the 1905 tests the concrete cubes were stored in air in a steam heated room where the temperature ranged from 60° to 70° F. Table 4 gives the compressive strength of 1-3-6 cubes of the 1905 tests. In the 1906 tests the concrete cubes were stored in sand which was kept moist during the period of storage. The results of the test are given in Tables 5 and 6. It will be seen that the values found are very high. In fact, these results are so much higher than other tests of concrete cubes made in this laboratory that the difficulty of comparing the tests with tests made at other times is increased. The cause of these variations is somewhat obscure; the manner of storing is probably only one of the elements

TABLE 6.

COMPRESSIVE STRENGTH OF 6-INCH CUBES.

1906 TESTS. 1-2-4 CONCRETE.

Ref. No.	Method of Storing	Age days	Compression Area sq. in.	Load in pounds		Compressive Strength lb. per sq. in.
				At First Crack	Ultimate	
	Damp sand	59	37.1	109500	128500	3463
6	Damp sand	59	37.1	110000	129000	3480
	Damp sand	59	37.8	73400	121400	3212
	Damp sand	59	35.6	96300	108000	3030
7	Damp sand	59	36.8	104000	117600	3193
	Damp sand	59	37.1	100600	120900	3259
	Damp sand	58	37.5	63400	124700	3322
8	Damp sand	58	37.8	99900	143100	3790
	Damp sand	58	37.8	86800	138000	3650
	Damp sand	59	36.8	79500	91900	2492
9	Damp sand	59	36.4	98000	113700	3120
	Damp sand	59	37.1	69300	99300	2675
	Damp sand	57	37.1	64000	111200	2998
10	Damp sand	57	37.5	59100	98600	2630
	Damp sand	57	37.5	84300	106500	3840

of difference. Tables 7 and 8 give results of the compression tests made on cylinders 8 inches in diameter and 16 inches long. These specimens were of the same material as the 1906 cubes and were stored in the same manner. It will be seen that the compressive strength determined from the cylinder is materially less than that obtained with the cubes. In all compression tests, a spherical bearing block was used, and a coating of plaster of paris was used on the bearing faces.

TABLE 7.

COMPRESSIVE STRENGTH OF 8 x 16-INCH CYLINDERS.

1906 TESTS. 1-3-6 CONCRETE.

Ref. No.	Method of Storing	Age days	Compression Area sq. in.	Ultimate Load pounds	Compressive Strength lb. per sq. in.
1	Damp sand	60	49.6	60500	1220
2	Damp sand	60	49.6	60000	1210
3	Damp sand	60	49.6	60000	1210
4	Damp sand	61	49.3	80400	1630
5	Damp sand	59	49.4	66200	1340
Average	....	....	....	....	1322
6	Damp sand	60	49.8	57800	1160

TABLE 8.

COMPRESSIVE STRENGTH OF 8 x 16-INCH CYLINDERS.

1906 TESTS. 1-2-4 CONCRETE.

Ref. No.	Method of Storing	Age days	Compression Area sq. in.	Ultimate Load pounds	Compressive Strength lb. per sq. in.
7	Damp sand	59	49.6	132000	2660
8	Damp sand	58	49.6	126000	2540
9	Damp sand	59	49.6	114000	2300
10	Damp sand	57	49.6	110000	2220
Average	....	....	....	....	2430

Discussion.—The behavior of the plain concrete plates and of the unreinforced recessed blocks during the test indicates that tensile stresses were the primary cause of failure with these forms of test specimens. This tension may be likened to the bursting stress developed in a cylinder subjected to internal pressure.

At a load of one-third to one-half of the ultimate load, hair cracks would appear at the bottom and middle of the exterior of the specimen. As the load was increased the crack extended upward and increased in width until at the ultimate load it attained a width of $\frac{1}{16}$ inch at the bottom and extended to the top of the specimen. The specimen could then be broken apart with the hands, giving four exterior pieces and the punched central core. The appearance of the crack is shown in Fig. 8. The broken specimens are shown in Fig. 7. The core which was punched out always showed cracks on the bottom and these generally extended one-half to two-thirds the distance to the top. In some cases the specimen broke into two parts as a beam fails, and in others the corners rose a small distance much as a metal plate does during a punching operation. In every case tension failure at the lateral faces occurred before shearing took place, and it was evident that the final, or ultimate, failure was much influenced by this condition and that ultimate failure could not be said to be due to simple shear. The recessed specimens were better in this respect than the plain plates, and the shearing stresses were evidently more nearly uniformly distributed throughout the depth with this form.

The reinforced recessed blocks failed in a manner quite similar to the unreinforced recessed blocks except that the cracks appeared relatively later and did not open up when the ultimate load was reached. The shearing loads were higher than for the unreinforced specimens and the conditions were more favorable for developing the shearing strength of the material. This is especially true where hoops were used for the reinforcement. An objection which still remains in this form of specimen is that the manner of applying the load at the top of the piece does not give an even distribution of the shear throughout the vertical section.

The manner of failure of the restrained beam form of specimen was as follows: In specimens No. 1 to 5 (1-3-6 concrete) and No. 6 (1-2-4 concrete) the first sign of failure was the appearance of cracks at the top as sketched in Fig 11 (a) at a load three-fourths to nine-tenths of the ultimate. These cracks seemed to be caused by a cutting action of the bearing plate or to tension due to beam action. As the load increased these cracks gradually lengthened and widened, as shown in Fig. 11 (b) until they finally reached a

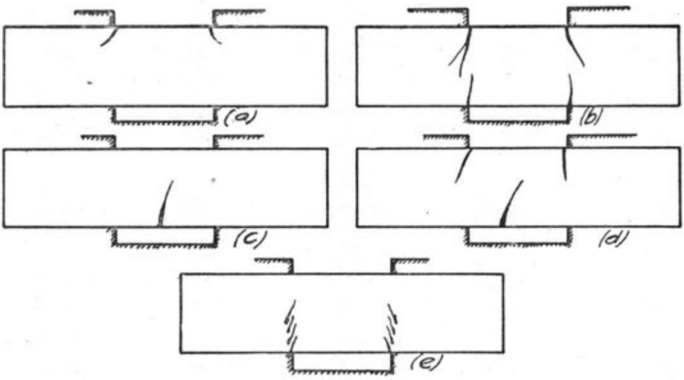

FIG. 11. MANNER OF FAILURE IN RESTRAINED BEAM SHEAR TEST PIECE.

TABLE 9.
SHEARING STRENGTH OF PLAIN PLATES.
1905 TESTS. 1-3-6 CONCRETE.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds		Shearing Strength lb. per sq. in.
				At First Crack	Ultimate	
39	Air	60	55.4	12000	37000	668
40	Air	60	56.5	18000	35000	620
41	Air	61	56.5	15000	39000	691
42	Air	61	56.5	28000	43500	770
43	Air	61	56.5	16000	36000	638
44	Air	61	55.4	14000	35000	632
45	Air	61	56.5	17000	42000	744
46	Air	61	56.5	18000	39500	700
47	Air	61	55.4	19000	36000	650
Average	....	....	....	....	....	679
31	Water	69	56.5	8000	36000	637
32	Water	69	54.2	15000	41500	765
33	Water	69	54.2	14000	38400	708
34	Water	61	54.2	12000	36200	667
35	Water	61	55.4	20000	47500	857
36	Water	61	56.5	13000	40000	709
37	Water	61	55.4	17000	42000	758
Average	....	....	....	....	....	729

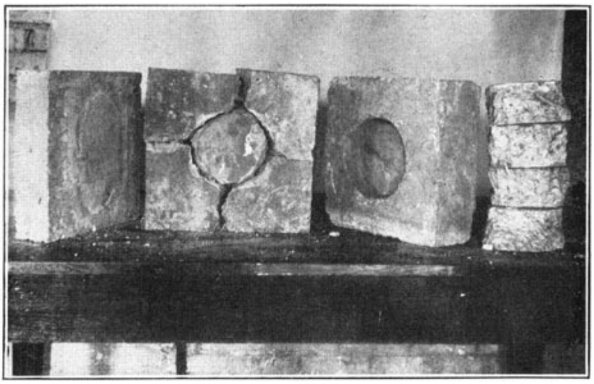

FIG. 7. VIEW SHOWING RECESSED BLOCKS AFTER FAILURE.

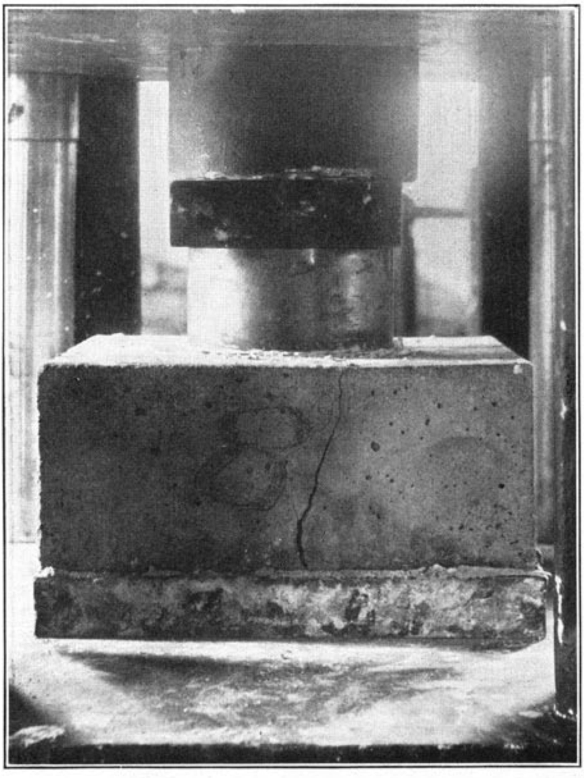

FIG. 8. VIEW SHOWING PUNCHING TEST.

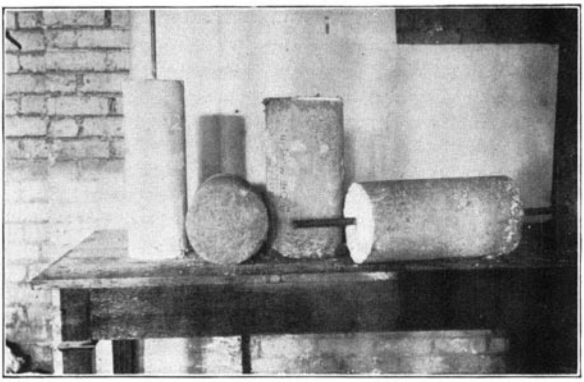

FIG. 9. VIEW SHOWING TEST PIECES.

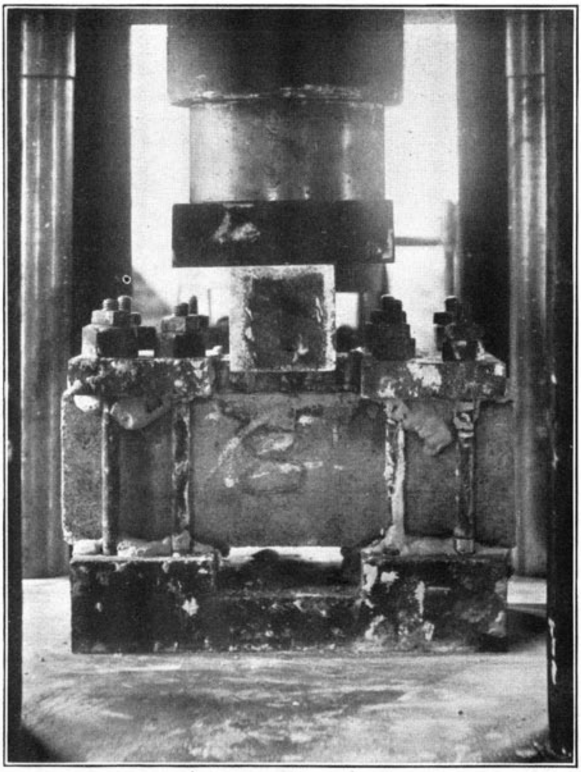

FIG. 10. VIEW SHOWING RESTRAINED BEAM SHEAR TEST.

TABLE 10.

SHEARING STRENGTH OF PLAIN PLATES.
1906 TESTS. 1-3-6 CONCRETE.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds		Shearing Strength lb. per sq. in.
				At First Crack	Ulti-mate	
1	Damp sand	60	57.8	28000	30800	533
2	Damp sand	60	61.0	18000	64500	1058
3	Damp sand	61	58.9	58000	60500	1028
4	Damp sand	59	60.1	37800	61200	1018
Average	....	....	....	....	....	909
5	Damp sand	60	61.0	39500	59000	968

TABLE 11.

SHEARING STRENGTH OF PLAIN PLATES.
1906 TESTS. 1-2-4 CONCRETE.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds		Shearing Strength lb. per sq. in.
				At First Crack	Ulti-mate	
6	Damp sand	59	61.0	24200	81000	1330
7	Damp sand	59	60.1	22000	86800	1443
8	Damp sand	58	58.9	16600	64500	1095
9	Damp sand	59	60.1	12800	48000	799
10	Damp sand	57	61.0	41800	79400	1300
Average	....	....	....	....	....	1193

maximum width, of, say, $\frac{1}{32}$ inch at the top. In specimens No. 7 to 10 (1-2-4 concrete) the first sign of failure was a tension crack as shown in Fig. 11 (c), which appeared at a load of one-third to four-fifths of the ultimate and gradually lengthened and widened as the load increased. Later cracks would appear at the top as shown in Fig. 11 (d). After the maximum load was reached, the lower crack gradually closed up and the upper cracks increased in width. The final shearing action occurred at a load less than the maximum and evidently took place over a much smaller shearing

TABLE 12.

SHEARING STRENGTH OF RECESSED BLOCKS.

1905 TESTS. 1-3-6 CONCRETE.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds		Shearing Strength lb. per. sq. in.
				At First Crack	Ultimate	
14	Air	60	56.5	23000	51000	903
15	Air	60	56.5	23000	36700	650
16	Air	60	55.4	30000	52500	947
17	Air	60	54.2	21000	34800	642
18	Air	61	56.5	....	39000	691
19	Air	61	55.4	24000	49500	894
20	Air	61	54.2	22000	52500	968
21	Air	61	55.4	26000	49000	894
22	Air	60	56.5	19000	47000	832
23	Air	60	56.5	....	37000	655
24	Air	60	56.5	23000	51500	911
25	Air	60	56.5	19000	41000	725
26	Air	60	54.2	14000	32500	600
27	Air	61	56.5	17500	45500	805
28	Air	61	56.5	18000	40500	717
29	Air	61	56.5	24000	50000	885
30	Air	61	55.4	22000	45500	811
Average	....	....	....	....	....	796
1*	Water	69	55.4	25000	39500	713
2*	Water	69	54.2	24000	33000	609
3*	Water	69	54.2	25000	36000	664
4*	Water	69	55.4	19500	43000	775
6*	Water	63	55.4	25000	37100	670
8*	Water	61	55.4	....	40000	722
Average		....	....	....	....	692
9	Water	61	54.2	20000	52500	968
10	Water	61	56.5	21000	47200	886
11	Water	61	56.5	24000	50000	885
12	Water	61	55.4	24000	53300	961
13	Water	61	54.2	22000	37700	695
Average	....	....	....	....	....	879

* These specimens were injured in removing the forms.

area than the full section of the beam. At the final failure of these beam specimens cracks formed as shown in Fig. 11 (e) through a portion of the depth. This portion of the vertical section evidently took the full shear.

TABLE 13.

SHEARING STRENGTH OF RECESSED BLOCKS.

1906 TESTS. 1-3-6 CONCRETE.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds		Shearing Strength lb. per sq. in.
				At First Crack	Ultimate	
1	Damp sand	60	58.8	54000	66300	1126
2	Damp sand	60	58.8	69400	69800	1187
3	Damp sand	61	57.8	63300	69300	1198
4	Damp sand	59	60.1	28000	63300	1052
Average	....	....	....	....	....	1141
5	Damp sand	60	60.1	42000	54700	910

TABLE 14.

SHEARING STRENGTH OF RECESSED BLOCKS.

1906 TESTS. 1-2-4 CONCRETE.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds		Shearing Strength lb. per sq. in.
				At First Crack	Ultimate	
6	Damp sand	59	60.1	39300	66200	1100
7	Damp sand	59	56.5	45600	82700	1463
8	Damp sand	58	57.8	41100	86500	1495
9	Damp sand	59	58.8	26200	74400	1262
10	Damp sand	57	57.8	19200	55900	967
Average	....	....	....	....	....	1257

TABLE 15.

SHEARING STRENGTH OF REINFORCED RECESSED BLOCKS.

1905 TESTS. 1-3-6 CONCRETE.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds		Shearing Strength lb. per sq. in.
				At First Crack	Ultimate	
48	Air	59	56.5	28000	47000	831
49	Air	59	56.5	36000	65800	1165
50	Air	59	55.4	50000	59000	1065
51	Air	59	56.4	52000	64500	1142
Average	....	....	....	....	....	1051

TABLE 16.

SHEARING STRENGTH OF REINFORCED RECESSED BLOCKS.

1906 TESTS. 1-3-6 CONCRETE.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds		Shearing Strength lb. per sq. in.
				At First Crack	Ultimate	
1	Damp sand	60	58.5	73000	89500	1529
2	Damp sand	60	57.8	98000	105500	1825
3	Damp sand	61	57.8	100000	108000	1869
4	Damp sand	59	57.8	62300	119100	2060
Average	....	....	....	....	....	1821
5	Damp sand	60	58.8	58200	91500	1555

Experimental Data and Discussion.

Data.—Tables 9, 10 and 11 give the results for the form of test piece called plain concrete plates. Tables 12, 13 and 14 give the results for recessed concrete blocks. Tables 15, 16 and 17 give the results for reinforced recessed concrete blocks. Tables 18 and 19 give the results for form of test piece called restrained concrete beam.

TABLE 17.

Shearing Strength of Reinforced Recessed Blocks.

1906 Tests. 1-2-4 Concrete.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds		Shearing Strength lb. per sq. in.
				At First Crack	Ultimate	
6	Damp sand	59	60.1	85300	145500	2420
7	Damp sand	59	55.2	37700	115500	2091
8	Damp sand	58	57.8	64300	160000	2767
9	Damp sand	59	58.8	56700	118000	2008
10	Damp sand	57	58.8	39300	84600	1440
Average	....	....	....	....	....	2145

Discussion.—Table 20 gives a summary of the shear tests, together with a comparison with the results of the compression tests. In considering the resistance of concrete to shearing action, as shown by these results, it will be well to take up the effect of the form of specimen upon the phenomena of failure, to consider the values obtained for ultimate failure and the elements which affect the shearing strength of concrete, and to compare shearing strength with compressive strength.

The tests bring out the difficulties of making shear tests. Even the best forms of test piece used proved not fully satisfactory for determining the strength of concrete in simple shear, and in particular their action does not conform exactly to the phenomenon as it exists in beam action. The tests throw light on the subject, and we may expect to be able to form a judgment on the shearing strength of concrete. In the plain plate test specimen the failure in tension caused by the bursting action evidently

TABLE 18.

SHEARING STRENGTH OF RESTRAINED BEAMS.

1906 TESTS. 1-3-6 CONCRETE.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds		Shearing Strength lb. per sq. in.
				At First Crack	Ultimate	
1	Damp sand	60	34.0	....	40500	1190
2	Damp sand	60	35.0	41200	48000	1371
3	Damp sand	61	34.0	46000	46500	1368
4	Damp sand	59	34.0	33300	45000	1324
Average	....	....	....	....	....	1313
5	Damp sand	60	34.0	34000	34700	1020

TABLE 19.

SHEARING STRENGTH OF RESTRAINED BEAMS.

1906 TESTS. 1-2-4 CONCRETE.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds		Shearing Strength lb. per sq. in.
				At First Crack	Ultimate	
6	Damp sand	59	35.0	....	54000	1543
7	Damp sand	59	34.0	31500	44000	1295
8	Damp sand	58	34.0	46400	58400	1718
9	Damp sand	59	34.0	33400	49300	1450
10A	Damp sand	57	34.5	29800	45800	1327
10B	Damp sand	57	34.5	27000	40500	1175
Average	....	....	....	....	....	1418

weakened the piece to resist shear, and the results are lower than the real shearing strength of the concrete. In the recessed blocks the bursting effect is distributed over a greater area. The reinforced recessed blocks resisted the bursting pressure even better. The 1906 test pieces reinforced with hoops showed the exterior cracks at a load well up to the ultimate load and these cracks did not open up when the ultimate load was reached. This form is the best of those used in the punching tests. Objection may be made to the punching test that the specimen does not have full opportunity to expand laterally, but a greater objection is that the shearing stress is not distributed uniformly over the shearing area. It is possible that in the specimen reinforced with a hoop the restraint interfered with shear action. The phenomena are further complicated by the compression put upon the test piece and its distribution. In the restrained beam form of test specimen, tension and cutting cracks decreased the effective shearing area. Besides, the application of the load at the level of the top of the beam does not permit an even distribution of the shear throughout the given vertical section. It seems evident that the real shearing strength of concrete will be greater than this form of specimen will give.

In discussing the results given in Table 20, the diverse nature of the materials, the methods of storage, and the form of specimen must be borne in mind. The stone used in the 1906 tests was harder than in the 1905 tests, and the concrete was much stronger. The air-stored specimens were weaker than those not exposed to drying out. The richer mixture does not give proportionally higher strengths than the leaner one. This is to be expected, since the strength of the stone must exert a considerable influence upon the shearing strength and may limit the resistance to shear. The higher values found in the tests made at the Massachusetts Institute of Technology in 1905, as compared with the 1904 results referred to in Taylor and Thompson's Concrete, are explained as due to the better quality of stone used. The quality of the cements used may have had something to do with the difference. It must be remembered that these tests are not entirely comparable. However, it would seem that the results of all these tests may be interpreted to mean that the shearing resistance of concrete is as high as, and probably higher than, the

TABLE 20.

SUMMARY OF SHEAR TESTS.

Form of Specimen	Year	Kind of Concrete	Method of Storing	Number of Tests	Strength lb. per sq. in.			Ratio of Shear to Compression	
					Shear	Compression		Cube	Cylinder
						Cube	Cylinder		
Plain plate	1905	1-3-6	Air	9	679	1230	...	.55	....
	1905	1-3-6	Water	7	729	1230	......	.59	....
	1906	1-3-6	Damp sand	4	905	2428	1322	.37	.68
	1906	1-3-6	Damp sand	1	968	1721	1160	.56	.83
	1906	1-2-4	Damp sand	5	1193	3210	2430	.37	.49
Recessed block	1905	1-3-6	Air	17	796	1230	......	.65	....
	1905	1-3-6	Water	6	692*	1230	......	.56	....
	1905	1-3 6	Water	5	879	1230	......	.71	....
	1906	1-3-6	Damp sand	4	1141	2428	1322	.47	.86
	1906	1-3-6	Damp sand	1	910	1721	1160	.53	.78
	1906	1-2-4	Damp sand	5	1257	3210	2430	.39	.52
Reinforced recessed block	1905	1-3-6	Air	4	1051	1230	......	.86	....
	1906	1-3-6	Damp sand	4	1821	2428	1322	.75	1.38
	1906	1-3-6	Damp sand	1	1555	1721	1160	.90	1.39
	1906	1-2-4	Damp sand	5	2145	3210	2430	.67	.88
Restrained beam	1906	1-3-6	Damp sand	4	1313	2428	1322	.54	1.00
	1906	1-3-6	Damp sand	1	1020	1721	1160	.59	.88
	1906	1-2-4	Damp sand	6	1418	3210	2430	.44	.58

* Specimens injured in removing the forms.

values found with the recessed blocks in the punching tests and with the restrained beam test. The shearing strength of this limestone concrete at 60 days, as determined by these methods, may then range from 800 to 1100 lb. per sq. in. for the stone used in 1905 and from 1100 to 1300 lb. per sq. in. for the stone used in 1906, both for 1-3-6 mixtures. For the 1-2-4 mixture with the stone used in 1906, the range is from 1250 to 1400 lb. per sq. in. These agree fairly well with the results obtained at the Massachusetts Institute of Technology in 1905. The reinforced recessed blocks of Table 17 give averages of 1768 and 2145 lb., so that the shearing strength may be higher than the results given above.

It seems evident that the shearing strength is far greater than the tensile strength and comparison of these two properties is not advisable. It does not seem profitable to compare shearing strength with compressive strength, since the former is more largely influenced by the strength of the stone and the latter by the strength of the mortar. The tests made with the recessed blocks, the reinforced recessed blocks, and the restrained beam test specimens indicate that the shearing strength is at least 50% as much as the compressive strength, except that the high results of the 1906 concrete cube tests bring some of the figures below this. These cube tests are much higher than any other of the same mixture made in the laboratory. Comparison with other cube tests and with the cylinders indicates that shearing strength may run well up toward compressive strength. A range which is thought to cover much of the concrete used is 50% to 75%. This conclusion would not disagree with the Massachusetts Institute tests nor with the conclusions of Feret.

Summary.—The following summary is offered:

1. It is difficult to devise a form of test specimen and a method of testing which will satisfactorily determine the resistance of concrete to shear. The difficulties lie in the inability to secure an even distribution of the shear over the shear section, in the high cutting and bearing stresses developed, and in the complications formed by the compressive, tensile, and bulging and bursting stresses developed. The forms of test specimen here used are not fully satisfactory, but information concerning the shearing resistance of concrete may be drawn from the tests as a whole, and tentative values selected. A test specimen in the form of a beam and in which the load is applied evenly over the depth of the beam instead of on the top is suggested.

2. The resistance of concrete to shear is dependent upon the strength of the stone as well as upon the strength of the mortar, and for the richer mixtures the strength of the stone probably exercises the greater influence. With hard limestone and 1-3-6 concrete 60 days old the shearing strength may be expected to reach 1100 lb. per sq. in., and with the 1-2-4 mixture 1300 lb. per sq. in. It seems very probable that the resistance to simple shear is considerably higher than this, and that tests made with the load applied evenly over the shearing section will verify this.

3. Since the compressive strength of concrete is influenced largely by the strength of the cement and the shearing strength is much more influenced by the strength of the aggregate, it does not seem proper to express the shearing strength in terms of the compressive strength. However, this is frequently done and is of advantage in gaining a conception of their relative action. It appears that the shearing strength is, in general, at least 50 % of the compressive strength, and that it may exceed 75 %. The apparent exception to this is explained by the high values obtained in the 1906 compression tests. These conclusions agree in a general way with the statement of Feret and others that the shearing strength is as much as two-thirds of the compressive strength. Evidently the shearing strength of concrete is several times its tensile strength.

II. BOND.

The tests of bond between steel and concrete, or tests of the resistance to a pulling force on the bars, were made in the manner usually followed in such tests. The concrete test piece was made small and short. The tests include the bond resistance of rods having smooth surface and uniform section, like cold rolled shafting, the effect of richness of concrete and of the depth the bar is embedded, and the resistance of flat bars. The work was done by Todd Kirk, a civil engineering student. Mr. Kirk had the misfortune to have the test specimens he made in 1905 injured in the accident mentioned in Bulletin No. 4. The experience gained gives greater reliability to the 1906 tests.

Materials.—The broken stone, sand and cement used were the same as hereinbefore described for the 1906 shear tests. Four different kinds of steel were used: $\frac{1}{2}$-in. and $\frac{5}{8}$-in. round mild steel rods having an elastic limit of about 38 000 lb. per sq. in.; $\frac{1}{2}$-in and 1-in. cold rolled shafting having an elastic limit of about 87 000 lb. per sq. in.; $\frac{3}{4}$-in. round tool steel having an elastic limit of about 53 000 lb. per sq. in.; $\frac{3}{16} \times 1\frac{1}{2}$ in. flat bars with an elastic limit of about 45 000 lb. per sq. in.

TABLE 21.

BOND BETWEEN STEEL AND CONCRETE.

1904 TESTS.

Test No.	Type of Rod		Maximum Load	Area sq. in.	Lb. per sq. in. of Net Section	Lb. per sq. in. of Net Surface	Elastic Limit of Steel	Remarks
1	½-in. Johnson		14990	.20	74950	625	60000	Concrete split.
2	"		14210	"	71050	593	"	" "
3	"	*	12605	"	63000	525	"	" "
27	"	*	15335	"	76650	639	"	Cylinder broke.
4	¾-in. Johnson		17175	.365	47050	573	58300	Concrete split.
30	"		11755	"	32200	392	"	" "
26	"		13975	"	38300	466	"	" "
5	"	*	16360	"	44800	545	"	" "
31	"	*	9515	"	26050	317	"	" "
32	"	*	8960	"	24500	298	"	" "
29	"	*	10435	"	28600	348	"	" "
33	⅜-in. square		4780	.16	29900	250	45000	Rod slipped.
34	"		6850	"	42800	357	"	" "
13	"		5850	"	36550	305	"	" "
35	"	*	6810	"	42600	357	"	" "
36	"	*	6910	"	43200	360	"	" "
18	"	*	4100	"	25600	214	"	" "
14	"	*	5560	"	34700	290	"	" "
8	¾-in. square		11600	.56	20620	322	35000	" "
9	"		11850	"	21100	329	"	" "
10	½-in. square		7910	.27	29320	317	33300	" "
15	"		6400	"	23700	256	"	" "
11	⅜-in. round		3255	.11	28800	228	42500	" "
12	"		3860	"	34200	270	"	" "
16	⅜-in. square	†	6905	.16	43150	180	45000	" "
17	"	†	6690	"	41800	174	"	" "
21	"		4785	"	29930	249	"	" "
22	"		6000	"	37500	312	"	" "
23	"		4580	"	28640	239	"	" "
28	"		6540	"	40800	340	"	" "
7	¾-in. round		7000	.452	15500	245	40500	" "
6	"		11000	"	27500	386	"	" "

* Struck 6 quarter-swing blows with a 10-lb. sledge.

† Embedded for a length of 24 in.

Test Pieces.—Two forms of test piece were used, one a cylinder 6 inches in diameter and 6 inches long, and the other 6 inches in diameter and 12 inches long. In Fig. 9 one of the vertical pieces is a bond test piece. The bars were embedded the full length of the cylinders, one end being left flush with an end of the cylinder and the other end projecting far enough to furnish a grip for the pulling head of the testing machine. The 6-in. length of encasement was used to make sure that the stress in the steel would be far below the elastic limit. It was planned that the stress in the steel in the 12-in. encasement should closely approach the elastic limit. In order to determine the effect of the quality of concrete, two mixtures, 1 cement– 3 sand– 5½ stone, and 1 cement– 2 sand– 4 stone were used, all by loose measure. The 1905 tests were with a 1-3-6 mixture.

TABLE 22.

BOND TESTS.

PLAIN ROUND RODS.

1-3-5½ CONCRETE.

Ref. No.	Diameter inches	Encased Length inches	Surface in Contact sq. in.	Maximum Load pounds	Running Friction pounds	Stress Developed lb. per sq. in.		
						Bond	Running Friction	In Steel
1	½	6	9.42	3400	1850	360	196	17300
2	½	6	9.42	3360	1900	356	201	17100
3	½	6	9.42	3510	1950	372	207	17900
4	½	6	9.42	3355	2000	377	212	18100
5	½	6	9.42	3640	2150	386	228	18500
6	½	6	9.42	3530	2050	375	218	18000
7	⅝	6	11.77	4300	3000	365	258	14000
8	⅝	6	11.77	4195	2600	358	221	13650
9	⅝	6	11.77	4250	2500	361	212	13850
10	⅝	6	11.77	4150	2650	352	225	13520
11	⅝	6	11.77	4075	2500	346	212	13300
12	⅝	6	11.77	4050	2950	342	251	13200
16	½	12	18.84	7130	5400	378	286	36400
17	½	12	18.84	7475	5300	397	281	38100
18	½	12	18.84	6500	4500	345	239	33100
19	⅝	12	23.54	10000	5500	425	234	32700
20	⅝	12	23.54	9500	6000	404	255	30950
21	⅝	12	23.54	8875	5000	377	212	28950

Method of Testing and Age of Test Specimen.—The free end of the bar to be tested was run through the movable head and held in the upper grips of the testing machine. The load was then applied with the movable head. In order that the pressure on the concrete might be uniformly distributed, a bearing plate bedded in plaster of paris was placed between the concrete and the movable head of the machine, the plaster of paris being allowed to set under a small load. The age of test piece when tested was 60 days.

TABLE 23.

BOND TESTS.

PLAIN ROUND RODS.

1-2-4 CONCRETE.

Ref. No.	Diameter inches	Encased Length inches	Surface in Contact sq. in.	Maximum Load pounds	Running Friction pounds	Stress Developed lb. per sq. in.		
						Bond	Running Friction	In Steel
42	½	6	9.42	4000	2470	425	263	20400
43	½	6	9.42	4490	2600	477	276	22900
44	½	6	9.42	4060	2400	428	254	20600
45	½	6	9.42	3840	1900	408	202	19600
46	½	6	9.42	3650	1700	388	181	18600
47	½	6	9.42	3340	1740	355	184	17000
34	⅝	6	11.77	5580	3400	475	289	18200
35	⅝	6	11.77	5510	3390	468	288	18000
36	⅝	6	11.77	5260	3600	448	306	17150
37	⅝	6	11.77	5530	3550	471	302	18000
13	½	12	18.84	8200	5500	436	292	41800
14	½	12	18.84	6820	5200	362	276	34800
38	½	12	18.84	7500	4500	398	239	24400
39	½	12	18.84	7900	4730	418	251	25700
15	⅝	12	23.54	11200	7500	476	318	36500
40	⅝	12	23.54	9040	4740	384	202	29450
41	⅝	12	23.54	9000	4000	382	170	29350

1904 Tests.—Table 21 is reprinted from Bulletin No. 1 and gives the results of bond tests made by Mr. Davis in 1904. The concrete used was a 1-3-6 mixture. In making comparisons the values with rods embedded more than 12 inches should not be used, since there is evidently an uneven distribution of bond stress over the length of the bar.

1905 and 1906 Tests.—Tables 22, 23 and 24 give the results of Mr. Kirk's tests. In Table 25 the results are summarized.

Results.—The condition of the concrete caused by the method of testing bond resistance here used, may be considered to differ from the condition of the concrete in a beam when bond stress is developed. In these tests the concrete specimen is subjected to compression, and this compression produces lateral expansion; this lateral expansion may increase the pressure on the surface of

TABLE 24.

BOND TESTS.*

VARIOUS TYPES OF BARS.

Ref. No.	Kind of Steel	Size of Bar inches	Kind of Concrete	Surface in Contact sq. in.	Maximum Load pounds	Running Friction pounds	Stress Developed lb. per sq. in.		
							Bond	Running Friction	In Steel
18	Tool	¾ round	1-3-6	14.13	2060	....	147	....	4650
19	steel	¾ round	1-3-6	14.13	2180	....	154	....	4940
20		¾ round	1-3-6	14.13	1993	....	141	....	4510
22	Cold	1 round	1-3-5½	18.84	2700	1500	143	80	3440
23	rolled	"	"	18.84	2200	1000	117	53	2800
24	shafting	"	"	18.84	2810	1270	150	67	3580
25		½ round	"	9.42	1425	550	151	58	7250
26	do.	"	"	9.14	1610	450	170	48	8220
27		"	"	9.42	1395	400	147	43	7130
28	Mild	$\frac{3}{16}$ x 1½	"	20.25	2260	1440	111	71	8050
29	steel	" "	"	20.25	2550	1700	126	83	9070
30		" "	"	20.25	2800	2000	138	98	9960

* In these tests the steel was encased to a length of 6 inches.

the steel and thus increase the resistance. On the other hand the low compressive stress developed, a maximum of 500 lb. per sq. in. at the top and 0 at the bottom, indicates that the effect of this can not be large.

TABLE 25.

SUMMARY OF BOND TESTS.

No. of Tests	Type of Rod	Size inches	Kind of Concrete	Encased Length inches	Surface in Contact sq. in.	Max. Load lb.	Bond lb. per sq. in.	Running Friction		Ratio of Running Friction to Bond
								Max. lb.	lb. per sq. in.	
6	Plain round	½	1-3-5½	6	9.42	3498	372	1983	210	57.0
6	do.	½	1-2-4	6	9.42	3893	412	2135	227	55.2
6	do.	⅝	1-3-5½	6	11.77	4170	355	2700	227	64.0
4	do.	⅝	1-2-4	6	11.77	5376	465	3485	297	64.0
3	do.	½	1-3-5½	12	18.84	7035	373	5066	268	72.0
4	do.	½	1-2-4	12	18.84	7605	404	4982	266	65.5
3	do.	⅝	1-3-5½	12	23.54	9458	402	5366	228	56.8
3	do.	⅝	1-2-4	12	23.54	9736	414	5284	223	54.0
3	Cold rolled shafting	1	1-3-5½	6	18.84	2570	136	1256	67	49.2
3	do.	½	1-3-5½	6	9.42	1476	157	466	50	31.8
3	Mild steel	$\frac{3}{16}$x1½	1-3-5½	6	20.25	2536	125	1713	84	67.1
3	Round tool steel	¾	1-3-6	6	14.13	2077	147	......	......	......

The following is given as an interpretation of the results of the tests:

1. Little difference is found in the bond resistance per square inch of surface of bar in contact with the concrete whether the bar is embedded 6 inches or 12 inches. Evidently a length may be found beyond which the stretch of the steel would cause uneven distribution of the bond stress along the length of the bar and cause failure to begin at the point of greatest stress in the steel and thus give results not representative of the real bond resistance. This limitation applies to length for use in experimental tests of bond. In simple beams the bond stresses are applied along the length of the bar, and stretch and bond exist together.

2. The richer mixture of concrete gives somewhat higher bond resistance than the leaner—the values for the 1-2-4 concrete averaging, say, 10% to 15% higher than the 1-3-5½ concrete. For plain round mild steel rods, the average for the bond resistance ranges from 350 to 450 lb. per sq. in. of contact surface.

3. The flat bars gave much lower resistance than round bars. Only three tests were made with flat bars, and these may not be representative. It may be noted that the results with flat bars are much lower than tests made elsewhere. It should also be noted that for a bond stress of 125 lb. per sq. in., the tensile stress developed in the bar was only 9000 lb. per sq. in.

4. The value of bond resistance will depend upon the smoothness of the surface of the bar, the uniformity of its diameter and section, the adhesive strength of the concrete, and the shrinkage grip developed in setting. The effect of smoothness of surface and uniformity of diameter and section is seen in the tests made with cold rolled shafting and tool steel. The average bond developed with cold rolled shafting and tool steel was 147 lb. per sq. in. of contact surface, as compared with about 400 lb. per sq. in. for ordinary plain, round, mild steel rods. It should be stated that not only was there a very noticeable difference in the smoothness and finish of the surface of the rods, but the section of the cold rolled shafting and tool steel was very uniform, the diameter not varying more than .0001 or .0002 in. at ¼-in. intervals throughout the length, while mild steel rods will vary as much as .0015 in. It is to be expected that the smoothness and uniformity of section of drawn steel wire will operate to give low values of bond resistance, though, of course, as the section of wire is small compared

with the circumference, the bond stresses developed when wire is used are relatively small. Attention is called to the fact that in the reinforced concrete beams described in Bulletin No. 4 the bond stresses developed in beams failing by tension of the steel, diagonal tension of the concrete or other similar methods amounted to from 73 to 193 lb. per sq in. Even at the breaking load, then, the bond stress developed in the mild steel rods was far below the bond resistance found in these tests.

5. In these tests the bars began to slip when the maximum load was reached. After slipping began, the resistance to motion was still considerable. This running friction, taken when the bar had moved about ¼ in., amounted to 54% to 72% of the bond developed in the case of mild steel bars and to 32% to 49% in the case of the cold rolled shafting.

PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION

Bulletin No. 1. Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904.

Circular No. 1. High-Speed Tool Steels, by L. P. Breckenridge. 1905.

Bulletin No. 2. Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905.

Circular No. 2. Drainage of Earth Roads, by Ira O. Baker. 1906.

Bulletin No. 3. The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906.

Bulletin No. 4. Tests of Reinforced Concrete Beams, Series of 1905, by Arthur N. Talbot. 1906.

Bulletin No. 5. Resistance of Tubes to Collapse, by Albert P. Carman. 1906.

Bulletin No. 6. Holding Power of Railroad Spikes, by Roy I. Webber. 1906.

Bulletin No. 7. Fuel Tests with Illinois Coals, by L. P. Breckenridge, S. W. Parr and Henry B. Dirks. 1906.

Bulletin No. 8. Tests of Concrete: I. Shear; II. Bond, by Arthur N. Talbot. 1906.